Baseline Assumptions and Ersatz Waste Streams for Partial Gravity Habitats with Mobile Female and Male Crew

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Effective and reliable water management and recovery systems will be required to support human missions beyond the low Earth orbit (LEO) of the International Space Station (ISS). Lunar and Mars surface missions will introduce new challenges to managing water and associated waste streams from mobile crew members who are transiting between up to six living shelters in extreme environmental conditions under a range of gravity conditions. A review of baseline assumptions for the human activities and associated air and water cycles in and between transit vehicle, orbiting station, lander-ascent vehicle, surface habitat, pressurized rover, and suits is conducted. The paper updates ersatz formulations and water flow rates for the main liquid water waste streams of urine, humidity condensate, hygiene, and laundry. Emphasis is placed on the metabolic emissions partitioning between the six vehicles during a design reference mission scenario. Ersatz to represent menses are reviewed.

Nomenclature

AES	=	Advanced Exploration Systems
BVAD	=	Baseline Values and Assumptions Document
CCAA	=	Common Cabin Air Assemblies
CM	=	crew member
CNSA	=	China National Space Agency
ConOps	=	concept of operations
DMSD	=	dimethylsilanediol
DWI	=	drinking water intake
ECLSS	=	environmental control and life support systems
ESM	=	equivalent system mass
FWR	=	fecal water rate
g	=	intensity of gravity force per unit mass, N/kg

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HC	=	humidity condensate
ISS	=	International Space Station
IWR	=	ingested water rate
LEO	=	low Earth orbit
LTV	=	Lunar Terrain Vehicle
MGH	=	Microgravity Habitat
MWR	=	metabolic water rate
N	=	newton
PGH	=	Partial Gravity Habitat
PSIA	=	pounds per square inch absolute
SH	=	Surface Habitat
TEE	=	total energy expenditure
TOC	=	total organic carbon
UPA	=	urine processor assembly
WHC	=	waste and hygiene compartment
WPA	=	water processor assembly
WRS	=	water recovery system
WTR	=	water turnover rate
xEMU	=	exploration extravehicular mobility unit

I. Introduction

NASA has plans to reestablish a human presence on the lunar surface through the Artemis Program. To date, 23 countries and the Isle of Man have signed the Artemis Accords, which are non-binding, multilateral agreements that provide a collaboration framework for exploring the Moon and Mars in sustainable and beneficial ways for humanity. In addition to NASA's Artemis Program, the Russian Federal Space Agency (ROSCOSMOS) and the China National Space Administration (CNSA) plan to construct the International Lunar Research Station (ILRS) to support human exploration of the Moon.

The key components of the Artemis program are the phased construction and occupancy of both an orbiting station (Lunar Gateway) and surface-based habitats to support exploration of the lunar surface. NASA and its international partners will utilize their experiences on the International Space Station since November 2, 2000, to design and build the lunar habitats' environmental control and life support systems (ECLSSSimilarly, China has gained recent flight experience with a crew of three occupying the Tiangong Space Station's ECLSS in low Earth Orbit (LEO) since June 17, 2021. Both NASA and CNSA have plans to build and occupy surface base camps near the lunar south pole in the 2030's.

This paper focuses on providing technology developers with expected quantities and composition of water and wastewaters distributed between the various Artemis habitation elements. Updated ersatz formulations and baseline values and assumptions are referenced from various sources to develop, test, and down select capable water-system architectures to support the Artemis ECLSS water management requirements. At the core of the ISS and the lunar habitats is the human water cycle associated with metabolism and physiological processes of each human inhabitant. In the case of the lunar missions, the humans will be moving their metabolic water cycle between several habitats. Hence, both the rate and composition of the human water influxes and effluxes and the timing and locations (time-mapping) of those water transformations become important for the optimal design configurations, synergies, and scheduled integrated operations of the lunar missions' water and waste management systems.

II. Habitat Elements

In this section, the major differences between the occupancy of the International Space Station habitat and the range of Artmesis habitat elements are discussed. A fundamental part of a remote human habitat is a reliable water system that stores, transports, collects, treats, and reuses water to support human health and crew activities in support of mission objectives in challenging environments. The ISS Water Recovery System (WRS) provides a well-established baseline habitat architecture to provide knowledge and a technological starting point for design of lunar habitats. The key differences between the ISS single-cabin atmosphere and the Lunar multi-habitat ECLSS are described in the following sections.

A. International Space Station Habitat

The International Space Station provides a single, well-mixed cabin atmosphere of about 800 to 900 m^3 with a nominal crew of 7. The ISS consists of a US orbital segment and a Russian orbital segment with well mixed air exchange. Each segment has a separate water and air management system. The low earth orbit of ISS at an altitude of 350 to 400 km and an orbital inclination of 51.6% results in elevated levels of ionizing radiation with associated formation of hydroxyl radicals in the cabin atmosphere that are difficult to simulate in ground testing.

During 2021 and 2022 calendar years, there were a total of 25 EVAs (averaging about two per month) with an average duration of 6.9 hours. The crew on ISS spends more than 99.7% of their time inside the ISS at the air pressure of 14.7 PSIA, 20 to 22 Celsius, and 40 to 45% relative humidity. The ISS Water Management subsystem consists of UWMS and WHC toilets, a urine processor assembly, a water processor assembly, a urine transfer system, a brine processor assembly, and a rack of four 73-liter potable and condensate water tanks (ICES-2022-98). The ISS has been occupied continuously without any uncrewed dormant periods since November 2, 2000.

B. Artemis Habitat Elements

An obvious difference between the Artemis lunar missions and ISS is the fact that the lunar missions will be 1,000 times farther away from Earth's surface than the ISS. The Artemis missions will also involve a number of small (~100 m^3) habitat elements at this distant destination, with the crew of four moving between the habitats to explore the lunar surface, with intermitted periods of dormancy on the order of one tp three years.[1] Up to six habitats will be utilized during a mission: the transit vehicle (Orion), orbiting station (Gateway), lander-ascent vehicle, surface habitat (SH), pressurized rover (PR), and xEMU suits for surface walking or riding in the lunar terrain vehicle (LTV). The fraction of time the Artemis crew spends conducting surface EVAs is expected to be similar to the Apollo Missions. For example, Apollo 17 crew spent 44 crew-member hours in suits walking or riding in the lunar rover, representing 5% of the total 905.6 crew-member hours of mission duration in space. Other challenges of the Artemis missions include a range of expected internal cabin pressures (ranging from 8.2 PSIA to 10.2 PSIA up to possibly 14.7 PSIA) and a range in the gravity vector from microgravity in the transit and orbiting vehicles to partial gravity on the lunar surface. Another long-term goal of the Artemis program is the mapping of the locations, abundance, composition, form, and depth of lunar water in the regolith. This will involve large variability in sunlight and darkness, challenging elevation changes, and big variances in thermal control requirements of habitats and the xEMU.[2]

C. Human Water Cycle – Quantities of Waste Streams

A significant habitation difference of note is that the ISS crew is stationed continuously within the ISS cabin, whereas the Artemis crews are mobile, transitioning from one habitat element to another, along with their own human metabolic emissions of water, carbon dioxide, and other waste products. In the case of ISS, all of the crew's water activities and waste streams are emitted in one habitat. An accurate time-mapping of the human water cycle as they transfer between habitats will be required to optimize the design and phased buildup of water processing capability and water closure with sequential Artemis Missions.

At the core of a space habitat's air and water cycles are the crew's metabolic processes and their physical activities within the habitat(s). The range of mass inputs and outputs of water for a crew member has been summarized.[3] In the following sections, we demonstrate a simple model of the metabolic emissions partitioning between the vehicles and habitats during a design reference mission scenario.

The human body partitions consumed and metabolic water into four main output "streams" based on a number of environmental conditions and activities. The four main output streams are water in sweat, respiration, urine, and fecal matter. Sweat and respiration are typically combined into "crew latent" in the air phase, with some partitioning of water onto clothing and towels that are allowed to dry in the cabin air or disposed of in the trash with small amount of water lost to trash.

Several key documents provide a range of basic requirements and guidance for microgravity and partial gravity habitats with humans metabolic processes and physical activities. These include NASA's Human Integration Design Handbook (HIDH),[4] NASA's Human Factors, NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health, (HFHEH),[5] and NASA's Life Support Baseline Values and Assumptions Document, (BVAD).[6]

Table 1 is a summary of basic relationships of different parameters with the inputs and outputs of water to the body. For the simple model used her to demonstrate the partitioning of human wastes into the various habitat elements, the "2-2-0.2" model is used, which represents a water output from the body of 2 kg/CM-day of crew latent (perspiration and expired water vapor), 2 kg/CM-day of water in urine, and 0.2 kg/CM-day of water in the fecal matter (ICES-

2022-388).[7] These values represent reference values, which can be adjusted with coefficients for the specific crew member's total energy expenditure (kcal/day), non-fat body mass, and the temperature and humidity of each habitat element. For the less active crew, the mass of urine will exceed the mass of crew latent. For more active crew, the mass of crew latent will exceed the mass of urine and the mass of fecal water will also increase relative to less active crew.[8]

Table 1 Water Turnover and Metabolic Energy Relationships for One Crewmember's Water Cycle

Parameter (kilograms-water/day)	**Equation (from Pontzer)**	**Range of Values, from Ewert and Stromgren 2019**[3]	**Values used in this paper's Time-Mapping Model**
Metabolic Water Rate (kg/day) =	0.00014 · TEE (kcal/day) 0.426 kg/day for 3054 kcal/day	MWR = 0.28 to 0.60 kg/day $MWR_{baseline}$ = 0.48 kg/day	**0.4 kg/day**
Ingested Water Rate (kg/day) =	Water Turnover Rate (kg/day) - Metabolic Water (kg/day)	IWR_{5th} = 2.78 kg/day IWR_{95th} = 5.35 kg/day $IWR_{baseline}$ = 3.05 kg/day	**3.8 kg/day**
Drinking Water Intake (kg/day) =	Ingested Water - Food Water	DWI_{5th} = 1.78 kg/day DWI_{95th} = 3.89 kg/day $DWI_{baseline}$ = 2.79 kg/day	**2.4 kg/day**
Water Turnover Rate (kg/day) =	WTR = Ingested Water + Metabolic Water = Urine + Perspiration + Respiration + Fecal Water	WTR_{5th} = 3.06 kg/day WTR_{95th}= 5.95 kg/day $WTR_{baseline}$= 4.53 kg/day	**4.2 kg/day**
Fecal Water Rate (kg/day) =	FWR = WTR - Ingested Water - Metabolic Water - Urine - Perspiration - Respiration	FWR = 0.120 kg/day[9] FWR = 0.225 to kg/day**Error! Bookmark not defined.** $FWR_{average}$ = 0.170 kg/day	**0.2 kg/day**

Notes:
Precise value of MWR varies with fat, protein, and fat intakes.
IWR values neglect transcutaneous and inspired water (< 40 g-water/day).
"baseline" = 82 kg male astronaut with 90 minutes exercise/day, TEE = Total Energy Expenditure = 3054 kcal/day baseline.[3]

D. Human Water Cycle - Composition of Waste Streams

1. Crew Latent (Humidity Condensate)

Crew latent provides the most easily recoverable water due to it's low ionic content and limited number of organic compounds. The presence of dimethlysilanediol, DMSD, in the ISS humidity condensate does present challenges and is capable of breaking through the WPA system. Several condensate ersatz are available (ICES-2021-76, ICES-2022-388, Verostko 2009). A new ersatz for both condensate and WPA Wastewater that includes trace nutrients to simulate worst-case biofilm growth has been developed for testing at MSFC (MBE document).

2. Urine

In most cases real urine is recommended for the test solution in order to include the unique composition and biological activity of urine. In early testing of technologies, ersatz may be used. It is recommended to add approximately 1 mL of real urine (collected from several donors) to 1 liter of ersatz to simulate realistic bacterial loading. For a worst-case urine, the 1 mL of real urine can be aged and aerated urine with bacterial capable of urea hydrolysis. In addition, albumin should be included in urine ersatz at 1o to 50 mg/L to provide foaming. Most urine ersatz do not include uric acid, since it is difficult to keep in solution. The inclusion or exclusion of uric acid and urates in ersatz should be noted as it can form precipitates in acidified urine.

3. Menses

The BVAD and NASA HIDH, 2014, provides baseline assumptions on menses quantities. An ersatz fluid was developed for testing as an artificial menses fluid. It consists of porcine red blood cells, egg white, and plasma (consists of about 90% water, fibrinogen, albumin, globulin, and salts) to provide the unique rheological properties.

4. Fecal Matter

The range and factors determining the water content and composition of water in fecal matter in microgravity and partial gravity is not well quantified and the fecal water content could be elevated by microgravity and physical activity by crew. A fecal simulant was developed with soy paste to simulate the water-holding capacity of feces. As is the case for urine, testing with real human feces is required for testing of flight hardware.

III. Crew Time-Mapping of Waste Streams

The partitioning of the three human main waste water output streams (humidity condensate, urine, and fecal water) into the various habitat elements is demonstrated for a crew of four during a 30-day surface Artemis mission. This scenario is simple version of a more detailed description of the challenging operating environments with the crew working in the surface habitat, the pressurized rover, and on surface EVAs provided in ICES-2022-196.[1] The four crew members will work in pairs during the surface stay with two occupying the SH while the other pair conducts EVA and traverse activities from the pressurived rover or lunar terrain vehicle. Other engineering and logistics challenges include lower total air pressure, partial gravity, contingency protocols, and extensive un-crewed and dormant periods. For this case, the water emissions from the body are based on daily average outputs.

For simplicity, only three habitat elements are included: the surface habitat, the pressurived rover, and the xEMU. A relatively limited numbers of six total surface EVAs of 8 hours each with a pair of astronauts is assumed for this demonstration. For the case here, the full crew of four stays in the surface habitat for one week at the beginning and the end of the 30 days on the surface. The time duration in the Orion, Gateway, and Lunar Lander are not included here, but could be added as the schedules are defined. The purpose here is to quantify the timing and locations of waste water production in order to design hardware and logistics to optimize the waste water collection system and water recovery system in phases. In this early assessment, the emphasis is on the amount of waste that needs to be stabilized and stored within each habitat element.

As the notional mission activities and habitat element occupancies become better defined, the rates can be converted to hourly rates of water emissions for specific activities, such as sleeping or exercising (Ewert and Strogren). At the core of the model is the occupancy duration and location schedule as shown in Figure 1. The cumulative occupancy in each of the three habitats is shown in Figure 2. We keep in mind that once the occupancy functions with time and space are known, all of the metabolic emissions may be superimposed to track emission locations. Those emissions are shown in Figure 3 (crew latent) and Figure 4 (urine). It is assumed, that unlike Apollo, no direct urine dumps to the lunar surface will be conducted during Artemis.

The cumulative mass of wastewater at 30 days may be used to size waste water collection bags or vessels and estimate required stabilization methods. The mass of condensate and urine are approximately equivalent in this simple model, so common containment vessels could be used for both condensate and urine. As comparison to the cumulative 30-day mass of 176 liters of condensate in the surface hab and 56 liters of urine in the pressurized rover (Figure 3), typical volumes for urine storage on ISS are about 20 liters and the CWC-Is are 0.13 mm (5 mil) Teflon® FEP film bladders that can hold up to 21.3 liters of water (ICES-2017-208).[10] The volumes and compositions could also be used to define requirements for a 30-day WPA to recover water from the humidity condensate, which is the cleanest waste stream and is most suitable for simple water treatment processes. In the case of urine, complete processing and dewatering (as is done on ISS) within the 30-day timeframe will be challenging without extending treatment into uncrewed water processing operations.

Figure 5 shows the cumulative water emissions to the lunar exosphere. In this example case, 56 kilograms of water will be emitted to the lunar exosphere. This quantifies the loss of the water to the lunar exosphere due to the current baseline assumption of the xEMU operations that utilize water evaporation for cooling and also emit crew latent.[2] Metabolic compounds (ammonia, methane, acetone, and other metabolic emissions) may be added to the water emissions to the lunar exosphere by mutiplying the nominal water quality (chemical composition) of the crew latent. This enables assessment of both water losses for the habitat and potential impacts on planetary protection requirements.

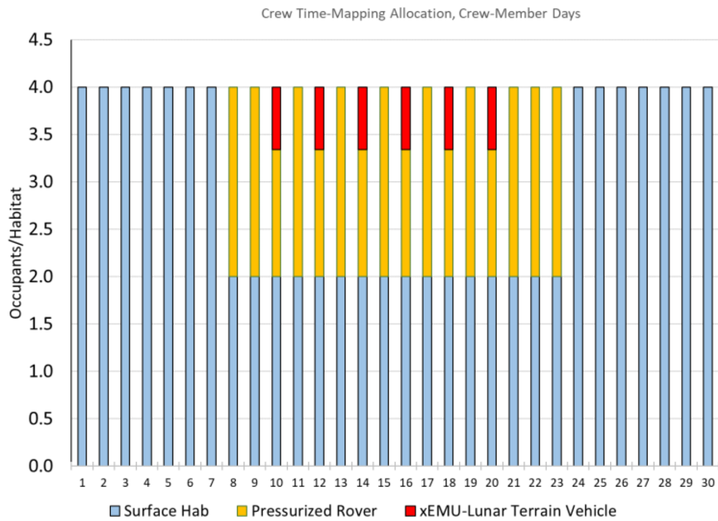

Figure 1 Crew Time-Mapping of Occupancy

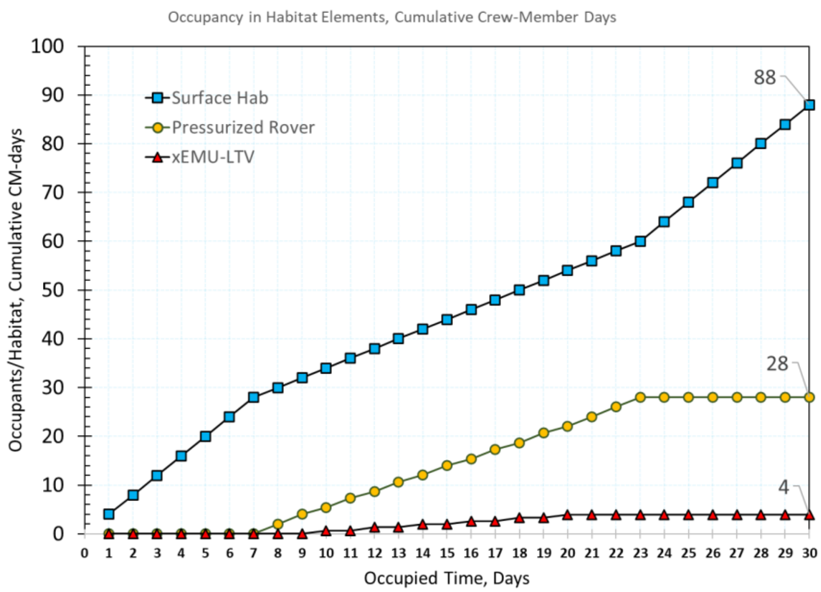

Figure 2 Occupancy in Habitat Elements

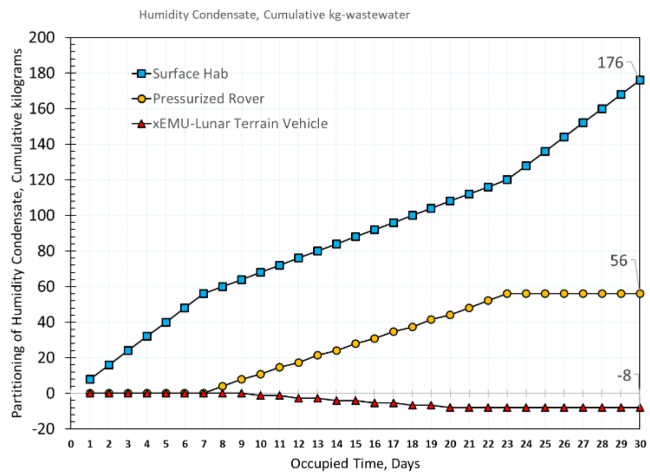

Figure 3 Time-Mapping of Humidty Condensate

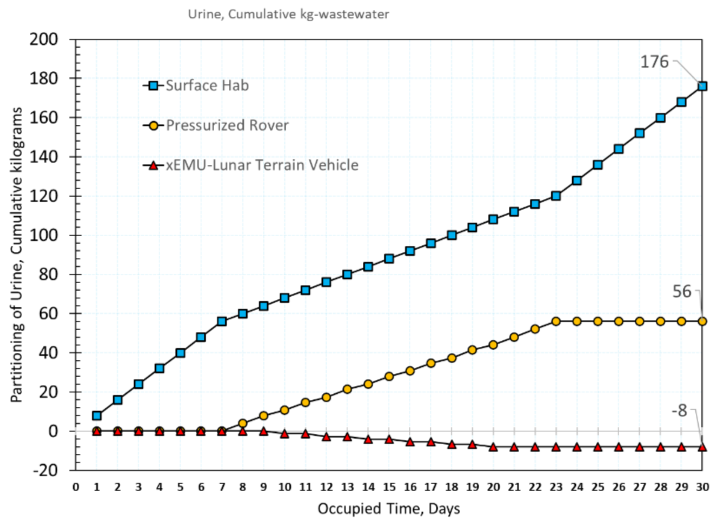

Figure 4 Time-Mapping of Urine

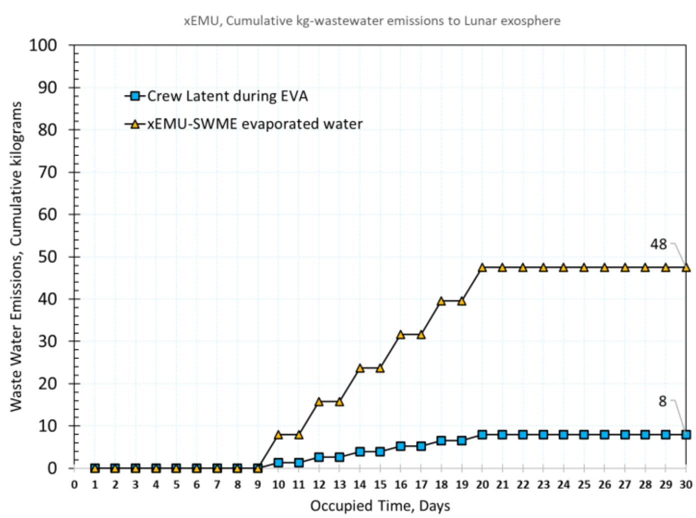

Figure 5 Time-Mapping of Emissions to Lunar Exosphere

IV. Knowledge Gaps

Based on the results of tracking the location and timing of the metabolic water emissions from a mobile crew on the lunar surface, some important distinctions between the experience and concept of operations on ISS and the activities on the lunar surface emerge. The ability to collect, stabilize, store, transport, and treat water and waste waters between habitats is of critical importance within and between the multiple habitat elements of lunar surface missions. New and simple methods of stabilizing wastewater with lower mass requirements than stabilizers used on ISS will be required along with simple vessels for waste storage that enable simple and reliable transfer between different surface elements. Similarly, the water recovery technologies will need to be simple, compact, and perhaps portable, with the ability to connect directly to the source of the waste water. Commonality of the water and waste systems components in each habitat will be required. The ability to utilize partial gravity for flows and treatment of water and wastewater offers potentially simpler designs than the heritage ISS water management system. The condensate collection, stabilization, treatment, and storage in the vicinity of the condensing heat exchangers will be the simplest water recovery step to implement, followed by urine water recovery and fecal water recovery. Unlike ISS, which operates the water recovery system continuously, the lunar water recovery system (the “30-day WPA”) will need to be designed to operate initially for 30 days and then be in a state of dormancy for a year or longer.

V. Summary

An evaluation and summary of the quantities and compositions of the main types of waste streams expected in future partial gravity habitats on the lunar surface has been presented. Time mapping of the humidity condensate and urine were presented for three habitat elements during one 30-day surface mission: the surface hab, the pressurized rover, and the xEMU. The cumulative mass of humidty condensate and urine were partitioned between the various habitat elements. Unlike ISS, the crew-time mapping of the human occupancy in each of several lunar habitats is the critical parameter for designing waste collection and treatment systems. This parameter determines the quantity and composition of each waste stream partitioning into the occupied habitats. In the case of the lunar EVAs, six EVA events with two crew members of 8 hours duration results in a water loss of about 56 liters to the lunar exosphere.

Acknowledgments

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